AD-A259 831

(1)

CENTER OF EXCELLENCE IN
COMMAND, CONTROL, COMMUNICATIONS AND INTELLIGENCE

GEORGE MASON UNIVERSITY
Fairfax, Virginia 22030

# QUARTERLY TECHNICAL REPORT

for the period

16 September 1992 - 15 December 1992

for

# THE IMPACT OF ORGANIZATION STRUCTURE ON TEAM DECISION MAKING UNDER STRESS AND UNCERTAINTY

Grant Number N00014-90-J-1680
R&T Project Number URI 5202-9003

DTIC
ELECTE
FEB 0 2 1993
S B D

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

Submitted to:
Dr. W. S. Vaughan, Jr. (3 copies)
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5000

Copies to:
Director, Naval Research Laboratory
Administrative Grants Office, ONR
Defense Technical Information Center

Submitted by:

**Paul E. Lehner**
**Alexander H. Levis**
*Co-Principal Investigators*

January 5, 1993

Report #: GMU/C3I-126-IR

93-01872

93

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
1/5/93

3. REPORT TYPE AND DATES COVERED
Quarterly Tech. Report 9/16 to 12/15/92

4. TITLE AND SUBTITLE
THE IMPACT OF ORGANIZATION STRUCTURE ON TEAM DECISION MAKING UNDER STRESS AND UNCERTAINTY

5. FUNDING NUMBERS
Grant Number
N00014-90-J-1680

R & T Project Number
URI 5202-9003

6. AUTHOR(S)
Paul E. Lehner and Alexander H. Levis

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center of Excellence in Command, Control, Communications and Intelligence
George Mason University
Fairfax, VA 22030

8. PERFORMING ORGANIZATION REPORT NUMBER
GMU/$C^3$I-126-IR

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The objective of the research reported herein is to investigate coordination in team decision making. Particular focus is placed on the identification and characterization of variables that enhance coordination and enable teams to maintain coordinated action under stressful conditions characteristic of tactical environments.

14. SUBJECT TERMS
Team Decision Making - Distributed Intelligence Systems - Belief Networks - Petri Nets

15. NUMBER OF PAGES
18

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified. | Unclassified. | Unclassified. | UL |

## 1. PROGRAM OBJECTIVES

The objective of this research is to investigate coordination in hierarchical team decision making. Particular focus is placed on the identification and characterization of variables that enhance coordination and enable teams to maintain coordinated action under stressful conditions characteristic of tactical environments.

## 2. STATEMENT OF WORK

The research proposal identified three major project tasks which define a sequence of three team decision making experiments. Each experiment involves the combined use of analytic models of the experimental setting and psychological models of human behavior to design the experiment and to predict performance.

*Year 1 Experiment* - The Year 1 experiment expands on the work of Jin (1990). The experiment will investigate the effects of time stress on team decision making performance. The experiment will be hosted on the testbed developed by Jin at MIT.

*Year 2 Experiment* - This experiment will focus on issues related to fixed versus variable structure organizations.

*Year 3 Experiment* - This experiment will extend the results of the previous experiments.

## 3. RESEARCH PLAN

The research plan describes our strategy for meeting the program objectives and fulfilling the project tasks. Specifically the research plan identifies a series of specific research tasks. As documented in previous progress reports, this research plan has evolved several times during the duration of this effort. It will likely continue to do so.

The plan for the first two years of this research program was organized into three highly related research areas:

(a) Analytical models of C3I organizations that incorporate coordination variables.

(b) Descriptive models of team decision making.

(c) Prescriptive models of team decision procedures.

As a result of our progress in these areas, a fourth research area was introduced in an earlier progress report that integrates the approaches in areas (a) and (c):

(d) Prescriptive models of adaptive C2 organizations.

This area is a natural evolution of the research program and represents an effort to merge together results from the cognitive and the engineering aspects of the research; this is the natural next step towards the development of a theory of C2 organization design that encompasses both fixed and variable structures.

Each of these areas is discussed briefly below. A detailed discussion of the individual tasks is provided in subsections 4.1 through 4.10.

The focus of the first area is the development of methodologies, models, theories and algorithms directed toward the derivation of tactical decision, coordination, and communication strategies of agents in organizational structures. Both fixed and variable organizational structures are considered. However, the focus is on modeling variable organizational structures and how those structures adapt under conditions of stress. The framework for this research is analytic. The following tasks address this research area:

4.1 Coordination in Decision Making Organizations

4.2 Design of Multilevel Hierarchical Organizations.

The focus of the second area is the development of descriptive models of human decision making that are relevant to predicting team decision making performance under stress. For this work, it is assumed that the team members are well-trained. Consequently, the focus of the research is to identify conditions under which team performance degrades because one or more team members cannot effectively execute trained procedures properly. The following tasks address this research area:

4.4 Experimental Research to Evaluate Vulnerable-to-bias Decision Procedures

4.6 Quantitative Models of Combined User/Decision Aid Performance.

The focus of the third area is to develop a prescriptive methodology for specifying team decision making procedures. This work combines the normative and descriptive research in the first two areas to develop a methodology for deriving a set of robust team decision procedures. This includes procedures for coordinating team decision making activities and adaptation of coordination procedures. In previous progress reports, the following two tasks where discussed under this research area.

4.3 Methodology for Prescribing Team Decision Procedures

4.5 Automated Tools for Specifying Decision Procedures

In an earlier report, a new research task was added.

4.10 Normative algorithms for generating adaptive team decision procedures.

Task 4.10 builds upon the results of Task 4.5, and addresses adaptation issues not addressed in the algorithms developed under Task 4.5.

The fourth area reflects an integration of the results obtained in the previous three research areas. Specifically, this research area addresses the problem of developing an integrated procedure that moves from an initial prescription of decision making procedures (research area 3) to a detailed analytic model of the organization (research area 1). To address this problem, that following research tasks have been added:

4.7 Petri Net Representation of Team Decision Procedure

4.8 Organizational Coordination Model

4.9 Integration of System and Coordination Models.

Each of these research tasks are described in detail in the next section.

The ten tasks that constitute the scope of work of this project are inter-related. with the tasks in area four building upon the findings of the other tasks. Their relationship to each other is



DTIC QUALITY INSPECTED 3

Avail and/or
Dist Special
A-1

shown in Figure 3.1. The four tasks in Figure 3.1, distinguished by the patterned boundary, are the ones that have been completed and reports have been written or are in the last stages of preparation.

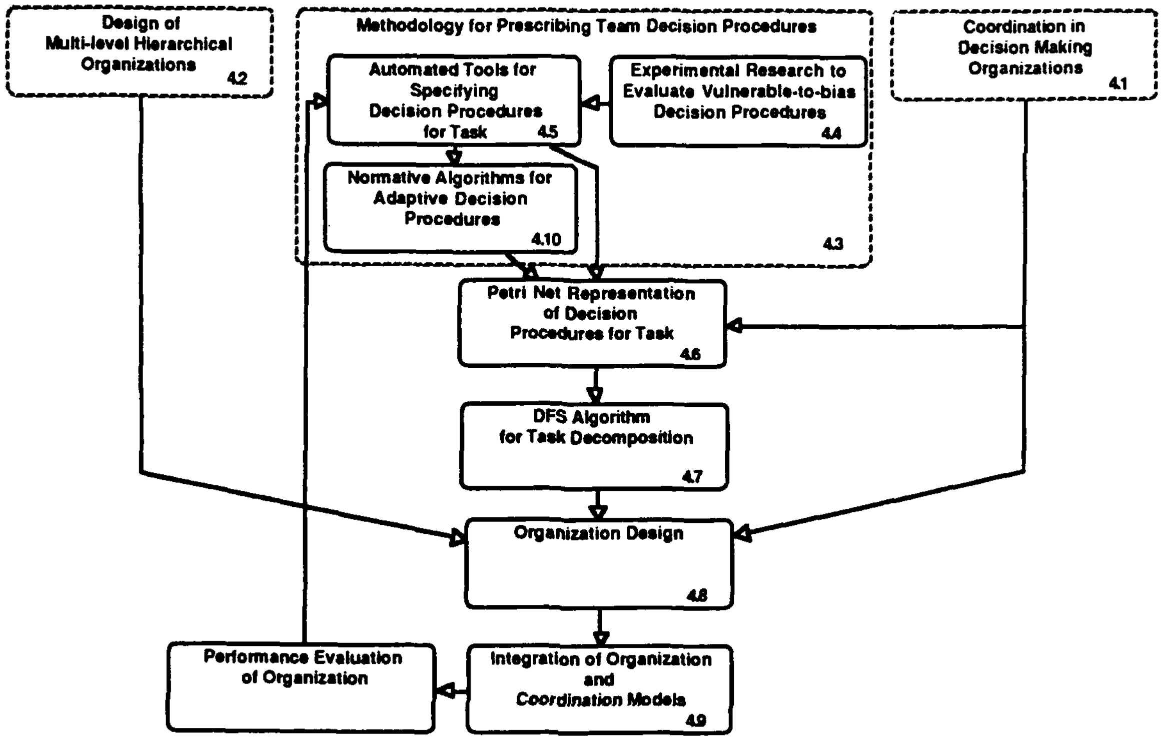


Figure 3.1 Inter-relationship of Research Tasks

## 4. STATUS REPORT

In the context of the three project tasks and research plan outlined above, a number of specific research tasks have been formulated. These are being addressed by project faculty and by graduate assistants under the direction of project faculty. Each research task is discussed below. In previous reports, detailed results for research tasks 4.1 through 4.4 were presented. In this report, we introduce three new research tasks 4.7 through 4.9.

### 4.1 Coordination in Decision Making Organizations

**Background.**

The concept of an organization embodies two meanings. One is the set of physical entities and the interactions between them. Another is the set of rules that govern the operation of a set of interacting physical entities. We call all these physical entities and their interactions the system, and we characterize the operation of the system as coordination.

A key question in modeling and designing organizations is whether these two concepts can be decoupled. Mr. Zhuo Lu has investigated this problem under the supervision of Prof. Alexander

H. Levis and has produced a Master's Thesis published as a technical report. This task is now complete. An effort is under way to edit the papers for submission to archival journals.

### Documentation

1. Z. Lu and A. H. Levis, "A Colored Petri Net Model of Tactical Decision Making," *Proc. 1991 Symposium on C2 Research*, National Defense University, Ft. McNair, Washington, DC, June 1991.

2. Z. Lu and A. H. Levis, "A Colored Petri Net Model of Distributed Tactical Decision Making," *Proc. 1991 IEEE International Conference on Systems, Man, and Cybernetics*, October 1991.

3. Z. Lu, "Coordination in Distributed Intelligence Systems," MS Thesis, Report GMU/C3I-120-TH, C3I Center, George Mason University, Fairfax, VA.

4. Z. Lu and A. H. Levis, "Coordination in Distributed Decision Making," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.

### 4.2 Design of Multi-level Hierarchical Organizations

**Background.** Both centralized and distributed organizations are characterized by their hierarchical structure. These organizational architectures are described by families of structures with each family concerned with the behavior of the organization as viewed from a different level of abstraction. Previous efforts under the Distributed Tactical Decision Making program resulted in a number of methodologies to design and generate architectures in which the system is viewed only from a single level of abstraction (Remy and Levis, 1988). The basic decision making entity assumed throughout these methodologies was a human decision maker (DM). This effort was directed towards a methodology to generate in some orderly manner organizational structures for *multilevel* hierarchical organizations. This research task was necessary if realistic decision making organizations are to be modeled and analyzed. A second benefit of this approach is that the dimensionality problem that prohibits the design of large organizations can be circumvented by solving a series of problems at different levels of abstraction. The research task has been carried out by Mr. Syed Abbas Zaidi under the supervision of Prof. Alexander H. Levis.

The following four issues have been addressed in order to implement such a methodology;

(a) The concept of multilevel hierarchical organizational structures was formulated analytically.

(b) A mathematical framework that is appropriate for the formulation of the design problem was identified.

(c) Sets of constraints were identified for different levels in the organization to reflect design requirements and to keep the problem of generating organizational structures computationally feasible.

(d) A set of connectivity rules were formulated in order to integrate organizational structures defined at different levels of abstraction.

**Results to Date**

This task has been completed. The research results are being rewritten in the form of a book chapter for inclusion in a new book by IEEE Press on Intelligent Systems Control.

**Documentation**

1. A. H. Levis, "A Colored Petri Net Model of Intelligent Nodes" *Proc. 1991 IMACS Symposium on Modeling and Control of Technological Systems*, Lille, France, May 1991. Also in *Robotics and flexible manufacturing systems*, J. C. Gentina and S. G. Tzafestas, Eds. , Elsevier Science Publishers B.V. (North Holland)1992.

2. A. H. Levis, "A Colored Petri Net Model of Command and Control Nodes" to appear in *Command, Control, and Communications: Advanced Concepts and Paradigms*, Carl R. Jones, Ed., AIAA Press, Washington DC. Book to appear in late 1992.

3. S. A. K. Zaidi, "On the Generation of Multilevel, Distributed Intelligence Systems using Petri Nets," MS Thesis, Report GMU/C3I-113-TH, C3I Center, George Mason University, Fairfax, VA. May 1992.

4. S. A. K. Zaidi and A. H. Levis, "Algorithmic Design of Multilevel Organizational Structures," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.

## 4.3 Methodology for Prescribing Team Decision Procedures

**Background**. A team is a well-trained group of decision makers with overlapping areas of expertise. Each team member has an area of responsibility, a set of decision functions for which that team member is responsible, and a protocol for communicating with other team members. Previous work in the mathematical modeling of teams has addressed the problem of specifying organizational structures, but there has been very little work addressing the problem of specifying the procedures embedded in each decision function.

In team decision making, a function corresponds to a set of decision procedures. For instance, a team member may be responsible for the function Interpret-Sensor-Readings, where it is the team member's responsibility to read a set of sensor displays (input) and to report values for Probable-Current-Situation (output). Another team member may be responsible for the function Allocate-Air-Resources, where it is the team member's responsibility to use information about the Probable-Current-Situation to determine how to allocate air resources.

The performance of a team depends on the decision procedures each team member has been trained to execute and how effectively and reliably those procedures are executed. The objective of this research activity is to develop an approach to prescribing a set of decision procedures that (a) will lead to high performance, and (b) team members can reliably execute even under conditions of high stress.

**Results.**

A general approach for prescribing team decision procedures was described in an earlier progress report and presented at the 1991 Symposium on C3 Research. In addition, the extension of this approach to include utility information was presented at the second annual review of the C3I Center in May 1992. In addition to specifying a general methodology, this task resulted in the identification of specific technical problems that must be solved in order to prescribe team decision procedures. Each of these technical problems, in turn, has been defined as an independent research task. Specifically,

Task 4.4: Experimental research to investigate vulnerable to bias decision procedures,

Task 4.5: Automated tools for specifying decision procedures, and

Task 4.10 Normative algorithms for generating adaptive team decision procedures.

Combined, these three tasks represent a decomposition of task 4.3. Consequently, it is no longer necessary to present technical results for task 4.3 separately. As stated in previous progress reports, the only remaining activity on this research task will be the preparation of a technical report describing the overall methodology, along with a summary of the results from tasks 4.4, 4.5 and 4.10. This will be prepared in the Spring of 1993.

**Documentation**

1. P. Lehner, "Towards a theory of team design," *Proc. 1991 Symposium on Command and Control Research*, June 1991, 149-159.

2. P. Lehner, "Towards a prescriptive theory of team design," *Proc. 1991 IEEE Conference on Systems, Man and Cybernetics*, September 1991, 2029-2034.

## 4.4 Experimental Research to Evaluate Vulnerable-to-bias Decision Procedures

**Background.** C2 teams are composed of a group of interacting decision makers working cooperatively to solve a common decision problem. Each team member has an area of expertise. Each team member is responsible for a distinct set of inference and decision functions for which each team members is well-trained. Under conditions of low stress, one would expect a well-trained team to reliably execute the procedures they have been taught and to perform well. An open question, however, is the extent to which training breaks down under conditions of high stress. Except for issues related to task workload, this issue has not been addressed.

The objective of this research task is to investigate the impact of cognitive biases on the performance of well trained teams under stress. Our research contrasts two perspectives.

*Perspective 1 (P1)* - Cognitive biases are largely a matter of preference. Although people tend to use heuristic rules that deviate from normative procedures, they can be taught to reliably use alternative rules, as long as the alternative rules do not exceed bounded rationality constraints.

*Perspective 2 (P2)* - Cognitive biases are largely a matter of capability. Even if trained, people do not reliably execute judgment and decision procedures that do not conform to cognitive biases.

For team decision making under stress, these two perspectives differ considerably with respect to their implication for designing teams. If P1 is correct, then the literature on human cognitive biases is simply irrelevant to the problem of designing teams. Properly trained and practiced teams will reliably execute correct decision procedures until workload or other bounded rationality constraints are exceeded. If P2 is correct, then cognitive bias considerations should place severe constraints on the design of a team. Specifically, one should avoid specifying team architectures and decision procedures that are inconsistent with the heuristic decision making procedures that people naturally use. Otherwise, these teams will be vulnerable to cognitive biases, and the team's decision procedure will not be executed reliably under high stress conditions.

Experiments investigating this issue will be performed.

**Progress to date.**

A report on the first experiment was distributed in May 1992.

The second experiment is being carried out by Mathew Christian under the direction of Dr. Lehner. The design and software implementation for the second experiment was completed during this period. Pilot studies were initiated.

**Documentation**

1. P. Lehner, B. Nallappa, M. O'Conner, S. Saks, and T. Mullin, "Cognitive Biases and Stress in Team Decision Making: Preliminary Report," *Proceedings of the 1991 Symposium on Command and Control.*

2. P. Lehner, M. Seyed-Solorforough, B. Nallappa, M. O'Conner, S. Saks, and T. Mullin. "Cognitive Biases and Time Stress in Team Decision Making." GMU-C3I Center Technical Report GMU/C3I-220-R, May 1992.

3. M. O'Conner, "Cognitive Biases: A Perspective and Recommendations." GMU-C3I Center Technical Report GMU/C3I-219-P, October 1991.

## 4.5 Automated Tools for Specifying Decision Procedures

**Background.** The objective of this task is to develop automated tools to *derive* team decision procedures from a domain model represented as an influence diagram. The automated tools will trade-off several factors in the specification of these procedures. These factors include expected performance, workload and cognitive biases.

This research is being performed by Azar Sadigh under the direction of Dr. Lehner.

**Progress to date**. The research in this task is being conducted by Azar Sadigh under the direction of Dr. Lehner. During a previous periods, analytic procedures for deriving team decision procedures were developed.

During this period, one of these algorithms (algorithm DD) was implemented. Using this tool, we will conduct a series of monte carlo studies to investisgate the complexity of near optimal decision procedures. It is our hypothesis that near optimal performance can be obtained with very simple inference procedures. If correct this hypothesis has strong implications for the design of C2 decision procedures, and the types of decision aids that could be provided to C2 decision makers.

**Documentation.**

1. P. Lehner, P. and A. Sadigh, "Reasoning under uncertainty: Some Monte Carlo results," in *Uncertainty in Artificial Intelligence: Proceedings of the Seventh Conference (1991)*, San Mateo: Morgan Kaufmann Publishers, 1991, 205-211.

2. P. Lehner, and A. Sadigh, "A procedure for compiling influence diagrams," in *Proceedings of the 1992 Symposium on C2 Research*, May 1992.

### 4.6 Quantitative Models of Combined User/Decision Aid Performance

**Background.** The literature on DSSs is replete with long lists of features of a "good" decision aid. Unfortunately, despite all this advice, there are very few models that purport to predict the effect that introducing a decision aid into an decision maker's setting will have on performance. This task will investigate the development of quantitative models of the impact of introducing a DSS into a team's decision process. This work is an extension of the result in Lehner. et al. (1990) and the methodology described in research task 4.3 for deriving team decision procedures.

**Results to date.** This work will be part of Mr. N. Thomas Lam's Ph.D. thesis. A general approach to modeling and predicting user/decision aid performance was presented at the C2 Decision Aids conference in June 1992.

**Documentation.**

1. Lam, N.T. and Lehner, P.E. "A Quantitative Model for Predicting the Usefulness of Decision Aids," *Proc. 1992 Conference on C2 Decision Aids*, Navy Postgraduate School, Monterey, CA, June 1992.

### 4.7 Petri Net Representation of Team Decision Procedures

**Background.** The objective of this task is to develop a methodology for deriving a Petri Net representation of the prescribed team decision procedure developed using the methodology described in research task 4.5. The resulting DTree is transformed into a Petri Net that represents the decisions to be made by the team and the information flow associated with the decision making process.

The work was carried out by Didier Perdu, Diwakar Prabhakar, Abbas K. Zaidi and Ms. Zhenyi Jin under the direction of Dr. Levis.

**Progress to Date:** The problem was formulated as follows: *Given a DTree representing the Team Decision Process, generate the fixed structure(s) describing the functionality of the tree.* The objective was to define a methodology to derive a physical architecture from a decision tree representing the sequence of decisions to be made by the organization.

An approach to solving this problem was described in the last quarterly progress report. No further work was done on this task. A technical paper documenting the results of this task is in preparation. It will become pert of the documentation of tasks 4.5 and 4.10.

### 4.8 Organizational Coordination Model

**Background.** Coordination involves a number of issues that are not readily apparent at the individual decision maker level. Of particular importance is the development of a coordination model that guarantees that input and transmitted information to be sufficiently informative that individual decision makers will adapt to the current decision situation and execute appropriate decision procedures. (This relates directly to the coordination constraint from task 4.1.) That is, the coordination model must specify an efficient adaptation strategy.

**Progress to Date:** The problem can be formulated as follows: *Given the fixed structures from Task 4.7, generate variable structure and check their feasibility.* Different folding schemes yield different variable structures. Protocols for folding the fixed structures into a variable structure must be specified. All possible folded structures, however, can be checked by the algorithm developed by Zhuo Lu in his thesis (Task 4.1), which checks the *coordination constraints,* The algorithm developed by Lu and documented in his thesis was coded in C on a Sun Microsystems Sparcstation by Lu and Ali Shah and was tested by Zaidi. The algorithms tests whether the coordination constraint in a variable structure organization is satisfied or not, and, if not, identifies the reason for the violation. The implementation of the algorithm provides an essential automated tool for testing variable architectures produced by the variable structure Lattice Algorithm proposed by Demaël in an earlier thesis and eliminating those that do not satisfy the contstraint.

The next step now was the recoding of the Lattice Algorithm so that it can be applied to variable structure architectures. This required the use of Colored Petri Nets in place of ordinary Petri Nets and the implementation of an algorithm for determining the S-invariants of Colored Petri Nets. The recoding and generalization of the Lattice Algorithm so that it can handle multi-level structures, as defined by Zaidi (see 4.2), and variable structures was being done by Zhenyi Jin under the supervision of Didier Perdu. The implementation of a new algorithm for obtaining S-invariants of Colored Petri Nets was done by Tong Zhang. The algorithm is based on the theoretical results obtained in 1991 by Chuang Lin and Tong Zhang.

Both these coding efforts represented major undertakings requiring a substantial number of hours; they were done primarilyduring the summer period because the graduate research assistants could dedicate uniterrupted time to the tasks, but required further work during this reporting period. The last aspect of the task, currently under way, is the implementation of a software architecture so that the various algorithms can work seamlessly with each other.

## 4.9 Integration of System and Coordination Models.

**Background.** Research tasks 4.7 and 4.8 result in a Colored Petri Net model of a variable structure that describes the prescribed set of team decision procedures. To complete the design, the tasks need to be allocated to Decision Making Units - either single decision makers or small organizational units. An interesting aspect of this work is that the model of Migration of Control (Levis and Skulsky, 1990) could be used to analyze how changes in the allocation of tasks to Decision Making Units affect organizational behavior. To perform the latter, existing algorithms for performance evaluation need to be modified.

This research is being performed by Mr. Didier Perdu under the direction of Dr. Levis.

**Progress to Date:** In the Petri Net representation of the feasible variable structures, task allocation is done by assigning transitions to decision making units (DMU). Adjacent transitions, belonging to one *branch* of the Petri Net, can be assigned to a single (DMU). However, tasks belonging to different branches cannot be allocated to the same DMU. Current research is focused on determining algorithms for task allocation.

In addition, a task that addresses a fundamental question in integrating the system and coordination models, namely, the consistency and completeness of the embedded rules, was initiated. This work is being done by A. Zaidi under the supervision of Dr. Levis.

The focus of the task is the development of a methodology for analyzing and correcting the set of decision rules used by an organization with distributed decision making. The methodology is based on the modeling of the distributed decision rules in the form of a Colored Petri Net and on the analysis of the net using s-invariant properties and occurrence graphs.

During this reporting period, the effort was directed on formalizing a suitable colored Petri Net representation of the set of decision rules. A simple Ordinary Petri Net representation was developed which can be used to transform decision rules represented in terms of propositional logic and/or in terms of a limited predicate logic representation, i.e., where all predicates are defined in terms of a single variable. Rules of the form; "$\forall x, \exists y$ s.t. p1(x) —> p2(y)", and "p1(x, y), p2(y, z) —> p3(x, z)" can not be adequately represented by this scheme, since the information content can not be modeled by ordinary PNs. Predicate/Transition (Pr/T) Nets (Genrich 1978) have been used by Du Zhang and Doan Nguyen for this purpose. The transformation of a set of decision rules into a Pr/T net was investigated. Following is an illustration of the method;

*Example*

Let the decision rules are given as follows;

**R1**: LIFTABLE(x) & STABLE(x) & OPEN-VESSEL(x) —> CUP(x)

**R2**: IS(x, light) & PART-OF(y, x) & ISA(y, handle) —> LIFTABLE(x)

**R3**: PART-OF(y, x) & ISA(y, bottom) & IS(y, flat) —> STABLE(x)

**R4**: PART-OF(y, x) & ISA(y, concavity) & IS(y, upward-pointing)
—> OPEN-VESSEL(x)

The rules R1 through R4 are transformed to their Pr/T net representation as shown in Figure 4.1.

The entire set of decision rules is obtained by unifying all the individual rules. The unification of the rules represent the causal relationship among the rules and facts of knowledge base. This method unifies the rules by merging all the places with the same predicate name. The Pr/T net shown in Figure 4.2 represents the entire set of decision rules (R1-R4).

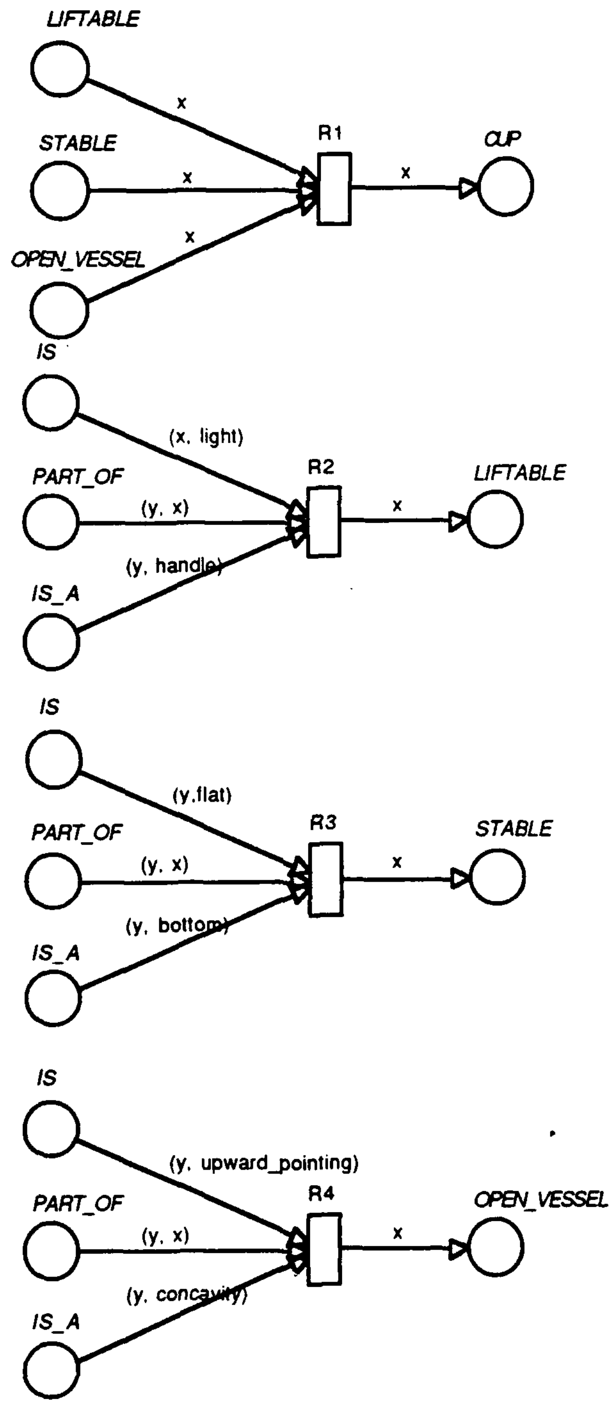


Figure 4.1 Predicate/Transition Net representation of the set of rules

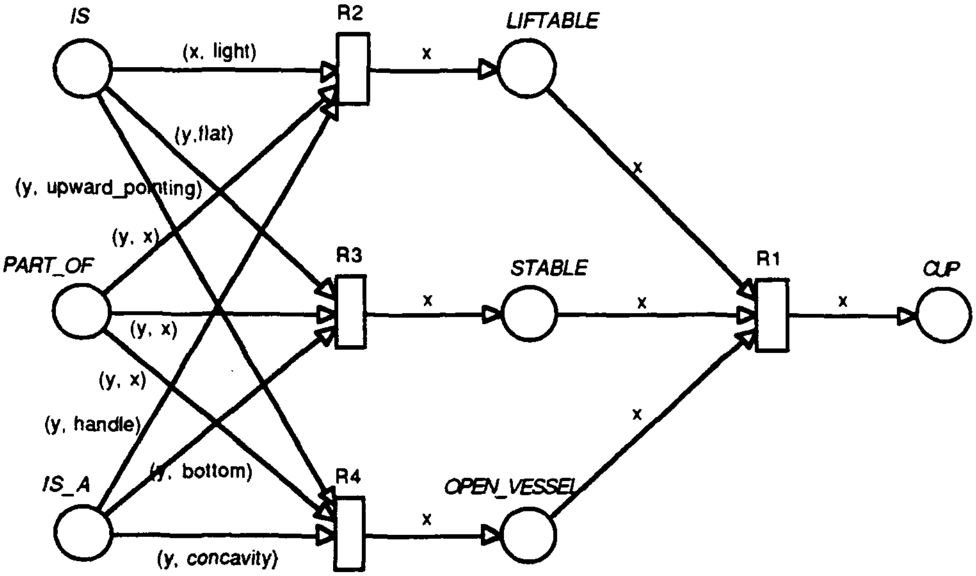


Figure 4.2 Single Pr/T net representing all the rules

The Pr/T net shown in the example is drawn by following the *Design/CPN* syntax, and is legitimate Colored Petri Net (CPN). During the investigation of a proper CPN representation of the decision rules, it has been a secondary objective that the CPN transformation be directly implementable on *Design/CPN*. The syntactic constraints imposed by *Design/CPN* create a number of implementation problems. In the illustrated CPN representation, Figure 4.2, the variable 'x' at an arc may or may not have the same value or 'type' as another 'x' at some other arc. In *Design/CPN*, the variables are *typed* and the simulator of *Design/CPN* does not allow the variable assignments shown in the illustration unless different occurrences of the same variable represent instances from the same *Color set.* At present, the effort is to resolve this problem, possibly by defining color sets in such a way that all variables represent the values from a single universal set - that will be consistent with the true definition of a variable as is used in rules. On the other hand, the different occurrences of a single variable do not pose any problem as far as the *bindings* of the transitions are concerned. The firing of a single transitions is a local operation and therefore the variable bindings of a rule do not affect the variable assignments of another rule as long as the variable assignments inside a rule are consistent. In order to illustrate the issue, consider the following two rules;

**R1**: P1(x, y) & P2(y, z) —> P3(x, z)

**R2**: P4(y, x) & P5(x, z) —> P2(y, z)

The rules shown above can be unified into a single rule as follows;

**R12**: P1(x, y) & P4(y, x1) & P5(x1, z) —> P3(x, z)

**R'12**: P1(x, y) & P4(y, x) & P5(x, z) —> P3(x, z)

Obviously, the rule R'12 is not the correct unification of the two rules: it may represent a specialization (subset of the instances covered by the two rules) of the correct unification R12, or in some cases it may not be true at all.

The CPN representation of the decision rules was investigated for such potential problems, and it was found that the local nature of the transition binding automatically takes care of such cases, and therefore, no pre-processing of the variables is required prior to the CPN transformation. However, identification of redundant sets of rules in a rule base does require a careful treatment of variables.

An algorithm for the determination of s-invariants by C. Lin and T. Zhang has been investigated in view of the this CPN representation. The s-invariant algorithm first calculates the s-invariants of the underlying Ordinary Petri Net and then finds the invariants for each *color* in the color sets. This algorithm is not directly applicable to the illustrated CPN representation, since the entire set of facts (colors) may not be available with the decision rules - as is the case in the example. Secondly, the problem of variables discussed above makes the calculation of colored s-invariants completely irrelevant. However, s-invariant analysis, if applied to the rules of the type illustrated in the example, still provides some insight into the rule base. This analysis does not unify the predicates, instead it merges all the input predicates into a single input, and then calculates the s-invariants of the underlying Ordinary Petri Net. The same procedure was found applicable to the kind of rules illustrated. However, no conclusive statement can be made at this time since a number of issues still need to be investigated.

### Documentation

None yet.

## 4.10 Normative algorithms for generating adaptive team decision procedures.

Task 4.5 has produced several algorithms for compiling a domain model into a DTree, which defines a *simple, near-optimal, complete* and *consistent* decision procedure. These algorithms provide a strong foundation for the development of a principled approach to prescribing/revising the decision procedures of a C2 team. However, except for adapting to time stress, the DTrees are not oriented toward adaptive decision making. This is because a DTree defines a tightly-couplied decisioin procedure. If one element of the overall procedure is disabled, then the rest of the procedure could also be disabled.

The objective of this research task is to enhance the algorithms develop in Task 4.5 so that they can generate team decision procedures that are robust and adaptive. Here *adaptive* means team decision procedures that can operate in a variety of circumstances beyond those for which the decision procedures were initially designed. *Robust* means that the adaptive decision procedure is near-optimal and simple-to-execute in these varied circumstances.

Examples of the types of adaptations we have in mind include the following:

1. Adapting to a change in information sources. For instance, when an important sensor (e.g., radar) is disabled, or the adversary is employing a new type of device for disrupting sensors (e.g., jammers).

2. Adapting to changes in the tactical environment. For instance, when it is realized that the adversary is engaging in a new tactic.

3. Adapting to changes in the command environment, such as when higher echelon command asserts new policies defining acceptable and unacceptable actions.

4. Adapting to changes in the general threat environment, such as when a situation moves from a peace setting to one involving potential hostile acts.

The general approach will be to introduce intervening variables into team decision procedures that naturally partition the overall team decision procedure into multiple, weakly-coupled miniprocedures that are organized into hierarchical layers. A weakly-coupled system of this type supports adaptation in several ways. First, if parts of the system are disabled, the remainder of the system is still be operational. Consequently, adapting to disabled sensors or communication is implicit in the procedure. No explicit change to the team procedure is required. In addition, a weakly-coupled system allows for many types of adaptation to be localized. For instance, adaptating to a policy change can often be achieved with just changes to the highest level procedures. Lower-level procedures, such as sensor interpretation, need not be affected. Finally, dynamic task reallocation is facilitated by weak-coupling.

Specifically, the general objective is to develop an algorithm(s) to derive a set of weakly-coupled decision procedures where (1) each decision procedure is simple-to-execute, (2) the combined effect of these procedures is near-optimal performance, and (3) degraded execution of a small number of the procedures does not result in poor overall team peformance.

**Progress to date**: Work on this task has just begun. The direction that this task will take depends in part on the results of the monte carlo studies discussed under Task 4.5 These studies will empirically evaluate the complexity of decision procedures needed to obtain near optimal performance. Clearly, the extent to which a decision procedure must be partioned depends on the complexity of that decision procerdure.

## 5.0 MEETINGS

Prof. Lehner attended the 1992 Symposium on C2 Research at the Naval Postgraduate School in Monterey, California. He also attended the 1992 IEEE International Conference on Systems, Man, and Cybernetics. He presented papers at both meetings.

Mr. Zhuo Lu and Mr. Abbas Zaidi attended the 1992 IEEE International Conference on Systems, Man, and Cybernetics and presented papers based on their completed theses.

## 6.0 CHANGES

Currently the grant for this research grant expires on March 15, 1993, which is in the middle of GMU's Spring 1993 semester. In order to allow students to complete their research under the auspices of this grant, we have requested formally a no cost extension until June 30, 1993.

## 7.0 RESEARCH PERSONNEL

### 7.1 Current Research Personnel

The following persons participated in this effort during this reporting period.

| | |
|---|---|
| Prof Paul Lehner | GMU - Co-Principal Investigator |
| Prof. Alexander H. Levis, | GMU - Co-Principal Investigator |
| Mr. Didier Perdu | GMU - Graduate Student (PhD) |
| Mr. N. Thomas Lam | GMU - Graduate Student (PhD) |

| | |
|---|---|
| Mr. Lee Wagenhals | GMU - Graduate Student (PhD) |
| Mr. Syed Abbas K. Zaidi | GMU - Graduate Research Assistant (PhD) |
| Ms. Tong Zhang | GMU - Graduate Research Assistant (PhD) |
| Ms. Zhenyi Jin | GMU - Graduate Research Assistant (MS) |
| Ms. Azar Sadigh | GMU - Graduate Research Assistant (MS) |
| Mr. Mathew Christian | GMU - Undergraduate Research Assistant |

### 7.2 Previous Research Personnel

The following persons were previously supported by the research effort.

| | |
|---|---|
| Mr. Zhuo Lu | GMU - Graduate Research Assistant (MS received) |
| Mr. Bhashyam Nallappa | GMU - Graduate Research Assistant (MS) |
| Mr. Diwakar Prabhakar | GMU - Graduate Research Assistant (MS received) |
| Mr. Ali R. Shah | GMU - Graduate Research Assistant (MS received) |
| Mr. Mir-Masood Seyed-Solorforough | GMU - Graduate Research Assistant (PhD) |
| Dr. Kent Hull | DSC |
| Dr. Martin Tolcott | DSC - Consultant |
| Dr. Theresa Mullin | DSC |
| Dr. Michael O'Conner | DSC - P.I. of subcontract |
| Mr. William Roman | DSC - Programmer |
| Mr. Steve Saks | DSC - Programmer |
| Dr. Michael Donnell | Consultant |

### 7.3 Personnel Changes

Zhuo Lu, Ali Shah, and Diwakar Prabhakar received received their MS degrees and left the program. Mr. Lee Wagenhals, Research Instructor, joined the research effort as a PhD student.

## 8.0 DOCUMENTATION

### 8.1 Theses

**Completed**

1. S. A. K. Zaidi. "On the generation of Multilevel. Distributed Intelligence Systems using Petri Nets," MS Thesis, Report GMU/C3I-113-TH, C3I Center, George Mason University. Fairfax, VA, November 1991. (Advisor: Prof. Levis)

2. Z. Lu, "Coordination in Distributed Intelligence Systems," MS Thesis. Report GMU/C3I-120-TH, C3I Center, George Mason University, Fairfax, VA, May 1992. (Advisor: Prof. Levis)

**In Progress**

3. MS Thesis by A. Sadigh - due May 1993. (Advisor: Prof. Lehner)

4. Ph.D. Thesis by T. Lam - due May 1994. (Advisor: Prof. Lehner)

5. MS Thesis by Z. Jin - due September 1993. (Advisor: Prof. Levis)

6. Ph.D Thesis by A. Zaidi - due June 1994. (Advisor: Prof. Levis)

## 8.2 Technical Papers


1. Lam, N.T. and Lehner, P.E. "A Quantitative Model for Predicting the Usefulness of Decision Aids," *Proc. 1992 Conference on C2 Decision Aids*, Navy Postgraduate School, Monterey, CA, June 1992.

2. Lehner, P. "Towards a Theory of Team Design," *Proceedings of the 1991 Symposium on Command and Control Research*, June 1991, 149-159.

3. Lehner, P. "Towards a Prescriptive Theory of Team Design," *Proc. 1991 IEEE Int'l Conference on Systems, Man and Cybernetics*, October 1991, 2029-2034.

4. Lehner, P., Nallappa, B., O'Conner, M., Saks, S. and Mullin, T. "Cognitive Biases and Stress in Team Decision Making: Preliminary Report," *Proceedings of the 1991 BRG Symposium on Command and Control.*

5. Lehner, P. and Sadigh, A. "Reasoning under Uncertainty: Some Monte Carlo Results," in *Uncertainty in Artificial Intelligence: Proceedings of the Seventh Conference (1991)*, San Mateo: Morgan Kaufmann Publishers, 1991, 205-211.

6. Lehner, P.E. and Sadigh, A. "A Procedure for Compiling Influence Diagrams," *Proc. 1992 Symposium on C2 Research*, Navy Postgraduate School, Monterey, CA, June 1992.

7. Levis, A. H., "A Colored Petri Net Model of Intelligent Nodes" *Proc. 1991 IMACS Symposium on Modeling and Control of Technological Systems*, Lille, France, May 1991. Also in *Robotics and flexible manufacturing systems*, J. C. Gentina and S. G. Tzafestas, Eds. , Elsevier Science Publishers B.V. (North Holland)1992.

8. Levis, A. H., "A Colored Petri Net Model of Command and Control Nodes" to appear in *Command, Control, and Communications: Advanced Concepts and Paradigms*, Carl R. Jones, Ed., AIAA Press, Washington DC. Book to appear in 1993.

9. Lu, Zhuo and A. H. Levis, "A Colored Petri Net Model of Tactical Decision Making." *Proc. 1991 Symposium on C2 Research*, National Defense University, Ft. McNair, Washington, DC, June 1991.

10. Lu, Zhuo and A. H. Levis, "A Colored Petri Net Model of Distributed Tactical Decision Making," to appear in *Proc. 1991 IEEE International Conference on Systems, Man, and Cybernetics*, October 1991.

11. Lu, Zhuo and A. H. Levis, "Coordination in Distributed Decision Making." *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.

12. Zaidi, S. A. K. and A. H. Levis, "Algorithmic Design of Multilevel Organizational Structures," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics,* October 1992.

13. Johannsen, G., A. H. Levis, and H. Stassen, "Theoretical Models in Man - Machine Systems and their Experimental Validation," *Proc. 1992 IFAC/IFIP/IFORS/IEA Symposium on Man-Machine Systems,* Pergamon Press, Oxford 1992: accepted for publication in *Automatica.*

14. Levis, A. H., Neville Moray, and Baosheng Hu, "Task Allocation and Discrete Event Systems," *Proc. 1992 IFAC/IFIP/IFORS/IEA Symposium on Man-Machine Systems,* Pergamon Press, Oxford 1992; accepted for publication in *Automatica.*

15. Lehner, P.E., "A Note on the Application of Classical Statistics to Evaluating the Knowledge Base of an Expert System," *IEEE Transactions on Systems, Man, and Cybernetics*, 1992, (to appear).

16. Lam, N.T. and Lehner, P.E. "A Quantitative Approach to Predicting the Usefulness of a Decision Aid," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics,* October 1992.